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A review on islanding operation and control for distribution network connected with small hydro power plant

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ABSTRACT

Hydro power generation is the oldest generation and provides the largest contribution among the renewable energy types of generation. In distribution system, most of the distributed generation (DG) is small scale hydro generation of which utilizes the natural flowing water of the river. This generation requires governor and excitation control unit to control and sustain the power generation when subjected to any changes of load behavior. More advanced control strategy is critically expected when considering the recent interest in distribution system to perform islanding operation of DG. Many of the literature have clearly highlighted this issue, but only a few have discussed on the islanding operation of small hydro generation. This paper therefore reviews this topic and relates the discussion with the controller designed for other type of turbines interfaced with synchronous generator. To strengthen the knowledge on islanding operation, the background of islanding is also presented in this paper.

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Contents

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1. Introduction

Over the last decades, numbers of distributed generation (DG) that are being connected to a distribution grid has substantially increased to meet an increased power demand from the industry. The DG are using renewable energy sources (water, solar, wind, biomass, etc.) and non-renewable sources (diesel, natural gas, etc.) to produce power which range from as low as 1 kW to as large as 1000 MW [1]. Their presence benefits the end user, the power utilities and the DG's owner in terms of reliability, efficiency of power, economics and etc. However, the interconnection of the DG with the grid changes the traditional power flow in a radial distribution system (from source to load) and thus affects the existing protection coordination setting. Moreover, the interconnection has emerged several technical issues. One of which is the islanding. Islanding or loss of main (LOM) is established when a part of the utility system (load section) is energized by the DG after being isolated from the rest of the utility system [2].

Considering the severe consequences islanding can bring, IEEE STD 929-2000 [3] and IEEE STD 1547-2003 [4] agreed that islanding should be prevented. However, benefits of DG will not be fully explored if the DG always needs to trip off every time the utility loses supply. With the high penetration level of DG expected in the near future, this tripping scenario is inappropriate and causes inconvenience for customers. Implementing an intentional islanding operation of DG will establish continuity of supply whereby the DG must be viable to take over the role of grid by independently feeding the whole island. Thus, this helps to improve reliability of supply to customers.

Realizing the benefit of intentional islanding could offer, in 2004, IEEE 1547 group has developed a draft series of guide referred as P1547.4 Draft Guide for Design, Operation, and Integration of Distributed Resource Island System with Electric Power System [5]. This document will serve as a guide for practicing an intentional islanding operation in electric power system.

Recently, there have been many research works reported on intentional islanding operation of DG. Most of the islanding operation were designed and modeled based upon the type of DG connected in the island. The DG can generally be categorized as rotating type and inverter type. For each type, different angles of research have been explored and tested. These research emphasized on achieving a good dynamic response during islanding operation. This factor helps to sustain the island within the power quality. To achieve it, the DG's controllers were designed specifically to operate in two modes of operation: grid connected and islanded. For synchronous DG, the dynamic response varies from turbine to turbine. Due to water inertia, a hydro turbine exhibits the slowest response than a diesel, gas and steam turbine when subjected to a disturbance or when the network is islanded. This has given researchers a challenge in designing a speed governor controller for the hydro turbine generator. The governor must capable to control the speed of the turbine so as the island frequency during transient condition is within the acceptable range of frequency protection setting.

Conventional governor such as mechanical-hydraulic and electro-hydraulic type with PID [6,7] are well known with their widespread used in the hydro power plant. However, these governors are unable to give their best performance for all operating condition particularly during transient. Over the years, to improve reliability, more advanced governor models for hydro turbine categorized as digital/electronics governors have been developed [8] to replace the conventional electro-hydraulic with PID. This governor's controllers have been designed/analyzed using several methods. Most of which using an adaptive control (i.e. using fuzzy logic [9,10]), intelligent control (i.e. artificial intelligence (AI)) and micro-controller based [11]. It is a normal practice to adopt this type of governor in facilitating various applications in an islanding operation.

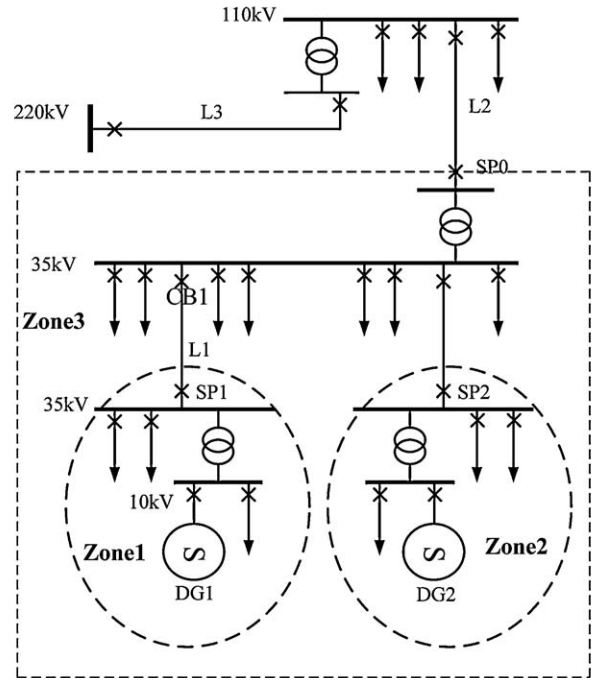

Fig. 1. An example of different zones of islanding area [12].

The primary objective of this paper is to review research works on intentional islanding operation for small hydro power plant. Since not many research works have described specifically on the control technique deployed for the hydro turbine governor to facilitate islanding operation, this paper extends the review on control techniques adopted for different types of governor(diesel and gas generator) which would be feasible for the hydro governor's application. The operation of single unit of DG as well as multiple and mix type of DG units are discussed. This paper will also presents an overview on islanding, islanding detection technique for rotating type DG and the current practice on islanding.

2. The background studies: islanding

2.1. Islanding formation

Islanding also known as loss of mains or loss of grid, is formed when a part of the distribution network that connected with a DG/DGs becomes electrically isolated from the utility supply but continue to be energized by the DG for supplying power to the loads. The formation is only possible with a condition that there is sufficient generation to meet the island loads. Otherwise, load shedding can be taken in place. A wider islanding coverage can be formed with a numbers of interconnected DGs in a distribution network. Fig. 1 illustrates an example of different islanding coverage (areas) which are formed with the opening of associate circuit breakers. The islanding area can be based of substation, one or more distribution feeder and voltage levels.

2.2. Concerns of unintentional islanding

Unintentional islanding is the state that one or more DG units unintentionally continue energizing a section of distribution network when the network loses supply. The system can be exposed to hazards and risks particularly when it is not being designed to

Table 1
Synchronization parameters limit for grid reconnection (to reconnect the island into the grid) [4].

Rating of DG (MVA)	Frequency difference (Δf, Hz)	Voltage difference (ΔV, %)	Phase angle difference ($\Delta\theta$,°)
0.0–0.5	0.3	10	20
>0.5–1.5	0.2	5	15
>1.5–10.0	0.1	3	10

support it. The following are several related issues regarding unintentional islanding [12]:

1) *Power quality*: This is the most important requirement for the utility in providing their customers a good energy supply. However, during unintentional islanding, the voltage and frequency can vary significantly and probabilities to be beyond the statutory limits are high. This can presents high risks to the loads and DG itself.
2) *Out of synchronism closure*: Out of synchronism closure is perhaps the most difficult issue to be addressed during formation of islanding. Most of distribution substation use auto-recloser in their protection system to improve availability of supply. When islanding occurs, the auto recloser will make several attempts to reconnect the island to the grid. As a result, they will be reconnected in out of synchronism. This is due to the mismatch of the phase angle, voltage magnitude and frequency for both energized system [13]. Those values must be within the acceptable limit before reconnection can occur. The well known impact of this is to rotating type of DG. The large mechanical torque and currents produced due to out of synchronism closure can damage the prime mover of the generator [14].
3) *Grounding or earthing*: During islanding, DG is separated from the main grid which therefore requires its own grounding/earthing connection. IEEE Standard 142-2007 [15] has set out regulation that allow multiple grounding for multiple power source (generator or transformer) connected in parallel. This does means that the islanded system has an earth connection connected to the DG. This is unlikely to be the case in the UK. Under current UK practice [16], it adopts single point earthing in which the earth connection is at the grid utility side [17]. Based on this practice, the DG can be left unearthed in the islanded system. This will presents high risks if the islanded section is energized by the unearthed DG.
4) *Protection systems on the islanded system are unlikely to be coordinated*: The presence of DG in the distribution network brings significant impact on the operation and coordination of the protection system. The DG might interfere the existing protection coordination with the change in fault current [18]. The same problem is encountered by the existing protection in the islanded system when the fault current change with the change in the network.
5) *Personal safety*: Personal safety is referring to the line worker that can be threatened by the disconnection of DG from the network. The operation of islanded system is beyond the control of the grid operator. During islanding operation, the line workers might not aware that the disconnected network is being energized by DG. This could present high risk to them if they still continuing maintenance works. The risks however could be prevented with a proper instruction of possible location of live network.

2.3. Current practice on islanding

As of today, it is not favorable to continue operate the islanded network which is isolated from the grid utility due to the hazards and risks (as discussed in Section 2.2) it can bring. It is stated in IEEE STD 1547-2003 [4] that for an unintentional islanding, the DG is prohibited to energize the island. The DG protections shall detect the occurrence of the island and then trip off the associate DG' circuit breaker (to shut down the DG) within two seconds of the island formation. Note that some utilities required fast detection of less than one second which is must be before auto recloser makes its first attempts of reconnection. This is depends on the protection coordination reclosing time of that auto recloser. For the detection, dedicated DG protections to detect and automatically shut down the DG are required. The protection of DG depends on the type of DG interconnected to the grid. The following is the typical protection for synchronous DG:

• 51 V: Overcurrent	• 59/27: Over/under voltage	• 81O/81 U: Over/under frequency
• 87: Differential	• 32: Reverse power	• 40:Loss of excitation
• 51 N: Earth fault time delayed overcurrent	• Loss of mains protection	

Even though islanding operation is prohibited, there have been many research efforts on intentional islanding operation. The movement is inspired with an increasing numbers of DG interconnected in distribution system. The DG is designed to operate islanded in order to improve service reliability to the customers. For the time being, regulation is being drafted by IEEE Working Group which is referred as IEEE 1547-4 (Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems). This regulation will be a guide for utilities or independent power producers (IPP) to design and operate islanded operation and carry out grid reconnection

Islanded operation can become a feasible solution when all the technical issues explained in Section 2.2 are resolved. The solutions and important requirements towards successful islanding operation which were highlighted in most of the literature are summarized as follows:

1) *Operation and management of islanded system*: A well planned islanding strategy is a primary requirement in performing a smooth islanding operation. The strategy shall include islanding detection technique, operation in grid connected and islanding mode and grid reconnection. Several strategies have been proposed for islanding operation of which were elaborated in [19–28].
2) *Generator controller*: This is the most important criteria in islanding operation. The controller is designed and modeled in two modes of operation: grid connected and islanding. In islanding mode, the controller should be able to maintain the power quality of the islanded system within statutory limit. To avoid out of synchronism closure during grid reconnection, the governor' controller of synchronous DG must be equipped with designated control unit to regulate the frequency, voltage and phasor of the island to be closely matched with those in the grid. The parameters limit recommended by IEEE 1547 is as illustrated in Table 1. Besides, the controller shall be able to improve the transient stability of the generator when subjected to loss of main. This including implementing load shedding when the demands exceed the generation capacity of the island. For multiple DG units, the load sharing control shall be introduced into the controller. The load sharing techniques are discussed in details in Section 3.2.3.
3) *Communication*: Fast and reliable communication link is required for transferring data and control information.

Examples of communication link usually adopted are as discussed in communication based techniques in Section 2.4.

2.4. Reviews on islanding detection technique-rotating type of DG

Islanding detection techniques is also known as Loss of Main (LOM) protection, anti-islanding technique and Loss of Grid (LOG) protection. There are basic requirements in designing a good and reliable islanding detection technique. The techniques shall be dependable, secure and fast in which it should be able to detect all types of islanding event considering various island behaviors and the detection time must be within a required time frame [29]. Besides, designing the islanding detection techniques depends on the characteristics of the DG unit. Generally, there are two types of DG: rotating type (synchronous generator and asynchronous generator) and inverter type DG. Each of the DG has different characteristics and operation principle. This is the reason why most of the techniques are developed merely for certain type of DG. Most of them are proposed either for synchronous generator or for inverter based DG application. This paper highlights islanding detection techniques normally utilize for synchronous types of DG.

Islanding detection techniques can be categorized into two main groups: remote and local [30,31]. Remote based on communication between the utility and the DG whereas local can be further divided into two main categories: passive and active. For small DG system, it is not advisable to apply remote techniques that are more expensive application than local techniques [30]. The performance of each type of detection scheme can be evaluated according to their non detection zone (NDZ). The NDZ is interpreted as the range of islanding load that the detection scheme fails to detect islanding [32–34]. Small NDZ depicts the effectiveness of the detection schemes.

2.4.1. Communication based techniques

Communication based detection techniques are based on information transferred between two or more locations via communication means to alert and initiate tripping signal to DG units upon detecting islanding event. These methods are very robust and reliable and do not have any issues on non detection zone. The only issue is they tend to be very costly to be practiced particularly for small DG units. A normal application is for larger generation scheme. These methods highly rely on the communication means, thus any communication failure will result in failure of islanding detection. The following are the common techniques using communication based:

1) *Inter-tripping*: It is also known as transfer trip is a communication connection between two or more locations in the network. In case of islanding detection, the communication is between distribution substation and DG units. If there is a trip in the substation, the tripping signal will be sent to DG units in the islanded network. One of its application is on SCADA system [29].
2) *Power line signaling*: This scheme uses the power line as a signal carrier [13]. The system mainly consists of transmitter and receiver. The transmitter is installed at the utility system. In principle, any signal transmits by the transmitter along the power line will be detected by the receiver. The receiver located at the DG side, will detect the islanding event when its fail to receive any signal from the utility. The signal is carefully selected to ensure reliable islanding detection. High frequency signal is attenuated to low frequency signal, at or below 500 Hz.
3) *COROCOF protection*: COROCOF is stand for comparison of rate of change of frequency. The scheme using similar concept as detection technique based on rate of change of frequency (ROCOF). The difference is that it compares the frequency changes in two locations in the network[35]. The result should be able to distinguish the changes of frequency due to loss of main with the changes due to other types of disturbance in the network by using a blocking signal. The COROCOF will trip if the blocking signal shows a difference in frequency measurement at the DG site with those at the utility network. The existing protection signal in the system such as radio signaling and power line communication is normally used in sending the blocking signal.
4) *Phasor measurement unit (PMU)*: This scheme requires two units of PMU of which one is located at utility side and the other one at the DG site. As proposed in [36], the voltage phasor is measured together with the time stamp at the utility. The measurement is compared with the one at the DG side. Any out of phase will initiate tripping of DG.

2.4.2. Passive techniques

Passive techniques detect islanding based on measurements of certain parameter [37]. If the measurements are not within specific thresholds, then they will decide to trip the system and to turn off the DG when necessary. The thresholds are set to avoid detecting other types of disturbance in the system. The most widely known passive methods applied for islanding detection are based on over/under voltage (OVP/UVP), over/under frequency (OFP/UFP) [38,39], rate of change of frequency (ROCOF) [40–43] and phase angle displacement(vector shift) [38,41,44]. Apart from that, several others proposed techniques applied are based on rate of change of active power [43,45], ratio of frequency variation to load variation [46], voltage magnitude variation [47] and change of total harmonic distortion(THD) of current [48]. In addition, several techniques proposed different approach which using more than one parameter to detect islanding:- rate of change of voltage and the change of power factor [49], voltage unbalance and THD of DG current [50], and frequency and damping factor of DG output frequency [34]. Two of which are suitable for both synchronous generator and inverter based DG application [34,50]. The primary drawback of these techniques is their detection performances would deteriorate with the reduction of active power imbalance (load and the DG generation are closely matched). This could result to a large islanding NDZ [38].

The following are brief descriptions of the most common types of passive techniques:

1) *Under/over frequency (UFP/OFP)*: In principle, under/over frequency relay trips the circuit breaker (CB) when the system frequency is under or over the standard limit setting. As for example, in the UK, underfrequency relay trip the CB of the generator when frequency drops below a lowest preset value (47 Hz) setting for time greater than time delay (typically 0.5–1.0 s).
2) *Under/Over voltage (UVP/OVP)*: Voltage relay is one of the protective devices used to prevent damage of equipment particularly the generator. It activates the tripping of CB in response to overvoltage or undervoltage event in which the value goes beyond the voltage limit setting of the relay. The standard limit normally applied is $\pm 10\%$ of nominal voltage. This threshold value is also used as an indicator of islanding event.
3) *Rate of change of frequency (ROCOF)*: In the UK, ROCOF relay is the most widely used passive islanding detection technique [51]. It operates based on the assumption that there is generation deficit following a loss of grid supply. This deficit or power imbalance causes transient which implies to a change of frequency. Thus, the rate of frequency changes (df/dt) has been considered as a measurement parameter for this type of relay to detect the islanding operation. This parameter is more reliable as compared to traditional frequency measurement particularly during a small power imbalance [41,42]. The rate of change of frequency is calculated over a certain number of measuring period (oper-

ating times) which is typically between 2 and 100 cycles. As for example, in the UK, ROCOF settings are normally between 0.1 Hz/s and 1.0 Hz/s with operating time between 0.2 s and 0.5 s [39].

4) *Vector surge relay (VS relay)*: Vector surge relay is also known as vector shift and phase angle displacement [41,52]. It detects an islanding event by monitoring the changes of phase angle for voltage across VS relay. When there is a loss of main, the rotor displacement angle of the DG changes with the changes of loads due to the islanding. As a result, the terminal voltage jumps to a new value with the phase position changes. The relay will initiate a tripping signal to CB when the change of voltage phase from its previous cycle is greater than the VS setting. Common setting is in the range of 6–12° [39].

2.4.3. Active techniques

Active techniques identify islanding event based on the response of DG when a small disturbance is injected to the system. The disturbances continuously vary the magnitude or frequency of voltage or current or the output power of the DG in which will create instability when an islanding occurs. Most of the proposed techniques have been implemented onto inverter type of DG [34]. The main advantage of active methods over passive methods is their small NDZ. The main drawback of these techniques is they can create power quality disturbance which eventually cause instability in voltage and frequency of the system. Meanwhile, the performance of this type of techniques may not be as expected when applied to multi DG [30]. The following are the two common techniques that have been implemented for synchronous DG application:

1) *Impedance measurement* [53]: Impedance monitoring method detects islanding based on the change of impedance considered from DG site when LOM occurs. This is from the fact that the impedance viewed from the DG increases when the DG is disconnected from utility network. However, the exact impedance value is difficult to measure. Indirect method is commonly used to measure the impedance value. They used voltage divider concept to measure the voltage output by injecting a small high frequency signal (HF) as the input to the voltage divider and connected to the mains via a coupling capacitor [53].
2) *Reactive power error export detection (RPEED)* [30,45]: The reactive power export error detection relay controls the DG excitation current so that it can generate certain reactive power flow at the inter-tie between the utility grid and DG site. The reactive power is continuously generated during normal operation of DG. Islanding is detected once the error between the setting and the actual reactive power persists for longer than the preset time period. This method is far more effective compared to passive methods when dealing with a small or no load change during islanding event. However, the slow operation time which is typically within 2 s to 5 s make them suitable to be applied as a backup protection system.

3. Research review

The introduction of smart grid in the last few years and an encouragement to maximize the usage of green energy have inspired researchers to develop more dynamic grid including an intentional islanding operation for renewable energy type (solar, wind, geothermal and hydro) of DG. Researches of interest on the islanding operation vary from country to country depending on the main energy sources most available in the country. For instance, wind power is the second largest renewable energy sources in the United Kingdom which contributes to more than one third of UK's current peak electricity demand (generate nearly 18GW of power) so far [54]. Thus, researches in wind generation including islanding operation are progressively carried out in the UK. Likewise, countries with tropical climate have driven their scientist to do solar energy researches. Conversely, hydro source is a common energy sources available in almost all countries, thus in the last four decades researches on hydro generation have been intensively carried out based on the corresponding design and consideration in each country. The research scopes are very broad including hydro plant design, turbine design, water intake design, modeling of governor controller, isolated operation, islanding operation and etc.

This section presents a review on accumulated research works regarding the islanding operation of small hydro power plant in a distribution system. In relation to that, a review on control strategies adopted for the islanding operation of rotating type of DG: (1) Single DG and (2) Multiple types/numbers of DG units operation is also presented.

3.1. Introduction of small hydro generation

Hydro generation have contributed to almost 19% of total power generation in this world [55]. The generation can be classified based on its capacity: large, small, mini and micro. As for small hydro generation, the size is varied from country to country where it is normally can be within 2 MW till 25 MW. The turbine used is mostly a type of run-of-river in which a little or no water is stored. This generation tends to reduce environmental impact since it is not required large dam to be built. This power technology are largely rely on its plant design and characteristics including the location of water intake, penstock, head size, water flows and the turbine types [56]. Those are the factors that affect the efficiency and maximum power output of the turbine. Out of these factors, one of the most important is the head size of the plant which is categorized as low, medium and high. In terms of cost effective per power output, the high head sites provide the most as compared to the low head sites. However, due to the structure of the river, small hydro plants are normally developed on low head.

Many of small hydro power plant are normally operated to serve customer in remote area and are not connected to the grid [57]. Without grid connection, this small hydro are not strong enough to hold the frequency and voltage within their permissible value which therefore require good governing and excitation system in its operation. The same applied for the small hydro to operate islanded when a part of the network is disconnected from the grid.

3.2. Controls for islanding operation

A good control strategy will ensure the stability of the islanded system. Control strategy of DG for islanding operation are normally classified into grid connected mode and islanding mode. When the DG is grid connected, the active and reactive powers (P–Q) are controlled and when the system is islanded, the voltage and frequency (V–f) are controlled. These control strategies have been implemented for both the rotating type and inverter type of DG [21,58,59]. With a large numbers of DG that are being interconnected to the grid, operation of mix type and multiple numbers of DGs in an islanding area is unavoidable. In this case, more complex controllers are required which would consider load sharing control and resynchronization with the grid.

For small hydro generation, synchronous and induction generator type of DG are commonly used. It is a fact that synchronous generator required a governor and an exciter to regulate speed and voltage of the machine respectively. For islanding operation, the governor regulates the speed and active power (P–f) whilst the exciter regulates the voltage and reactive power (Q–V). Islanding causes a change in the load (power imbalance) thus result in a change in the frequency (based on the swing equation). The

frequency deviation following a transient (due to islanding) is of a big concern as it would easily trip under or over frequency relay thus bring the generator to halt and unable to sustain the islanding operation. This is the main reason for the literature reported more on governor design where several approaches were tested and evaluated. During islanding operation, the governor should be able to regulate the frequency within permissible limit and fulfill the grid resynchronization requirement. Meanwhile, the exciter is used to regulate the voltage to be within the limit (typically within ±10%). On the other hand, induction generator has a simpler design and cheaper in cost than a synchronous generator. Islanding operation is possible with this generator provided that the external voltage source is equipped. The external source such as a switched capacitor bank or a synchronous machine helps to supply reactive power to the island.

This section elaborates the islanding control strategies commonly adopted for synchronous DG. This includes the speed and active power control (for the governor) and voltage and reactive power control (for the excitation system). The design of hydro turbine which has considerable effect to the governor response is also highlighted. The operation of multiple parallel connected DG units considering the load sharing technique deployed among the DGs during islanding operation is also discussed.

3.2.1. Speed and active power control

The correlation between the speed and the active power of a synchronous generator can be explained by the swing equation as follows:

$$2Hs\Delta w_s = \Delta P_m - \Delta P_e \tag{1}$$

where H is the inertia value of the generator, ΔP_m is the changes of mechanical power which is controlled by the governor, ΔP_e is the changes of electrical power due to the changes of the load demand, Δw_s is the changes of the speed of the generator.

From the equation, it is obvious that the changes of speed are proportional to the changes of active power. Large power imbalance will result of large speed deviation which will trigger the relay protection if the frequency is over or under the threshold value. It is important to point out that the inertia value of the generator, H could reduce the speed deviation. The higher the inertia value, the better the speed transient response will be. The inertia value depends on the capacity of the machine itself. When the system islanded, the immediate response of speed due to power imbalance and inertia will first affect the transient response of the DG followed by the response from the governor controller. Thus, a proper consideration prior to intentional islanding operation including the expected power imbalance is required in ensuring a seamless and safe islanding operation.

The governor controller is well known with its role to manage the active power and speed of the synchronous generator type of DG when it is grid connected and islanded operation respectively. There are three type of governor controllers namely fixed, droop, and isochronous [60]. For an islanding operation, a fast, robust and reliable governor such as a digital governor is required.

To be able to operate islanded, several approaches have been proposed in designing the governor's controller. The complexity of the controller varies with the numbers of DG connected in parallel to the distribution network. Combination of different capacities of DG, turbine and type of DG reflects the controller design. For single unit of DG connected to the grid, common approach is to employ a fixed/droop control mode when the system is grid connected and switch to an isochronous mode when the system is islanded. For fixed control modes, fix value of active power need to be specified. Isochronous controller which is also called as an integration controller helps in eliminating steady state error and restores the speed of the DG to its nominal value. Fig. 2 shows an example of isochronous controller in PID controller.

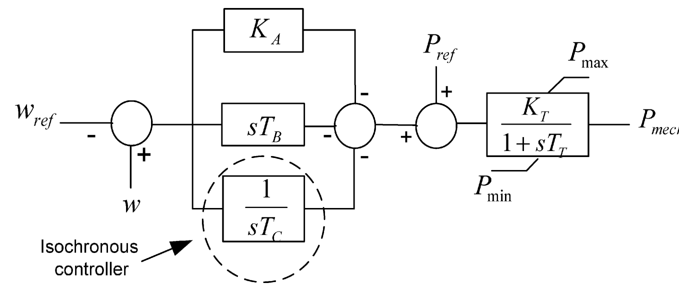

Fig. 2. Isochronous controller [62].

As previously stated, other than frequency and voltage, phase angle is one of the factors required for grid resynchronization. It is important that the voltage phase angle at the point of connection between the grid and island to be as close as possible with a maximum difference value of 25–40°. This is due to avoid out of phase synchronism re-closure. It is proposed in [61] that the phase angle is controlled together with the speed by using the governor. The proposed control diagram is as shown in Fig. 3. Using this controller, grid resynchronization process can be done autonomously.

For synchronous type of DG, the dynamic response of the governor is fed to the turbine which is then produced torque for the generator. Note that the type of turbine has considerable effect on the speed response of the DG. For hydro turbine, most of the literature considered a simple first order linear model in their study. The transfer function for this turbine model is formulated as follows [6]:

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - sT_W}{1 + s0.5T_W} \tag{2}$$

where T_W, water starting time; P_m, mechanical power for turbine; G, gate position.

The water starting time is normally varies from 0.5 s to 4.0 s [6]. The time is to represent the time taken for a head to accelerate the water from standstill to an initial velocity. The longer the time taken, the slower the response will be. Other than turbine, the opening/closing rate of the valve for the gate also presents significant effect to the speed response. Fig. 4 shows an example of hydro governor turbine model used in one of the studies [62]. More advanced hydro turbine models for dynamic studies considering from a simple model to complicated models were presented in [63].

3.2.2. Voltage and reactive power control

The voltage and reactive power are closely relates one another that the controller of excitation system is modified to control both parameters for an islanding operation. The concept introduced in one of the literature is to control reactive power to a value of zero [58] when the distribution network is grid connected and control the voltage level to its reference value when the networks is islanded. To control the voltage is not as critical as to control the

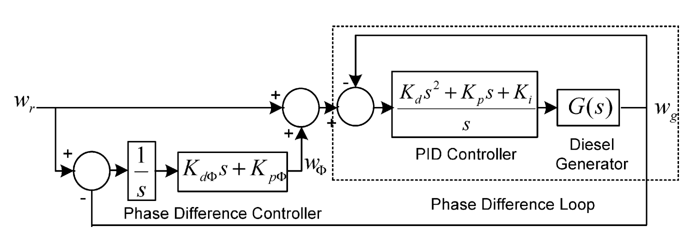

Fig. 3. Phase controller [4].

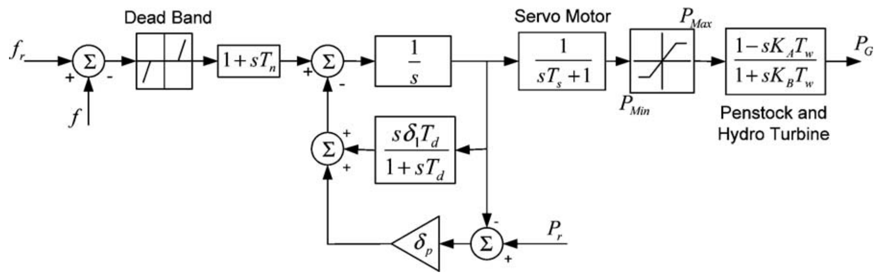

Fig. 4. An example of hydro governor turbine model [64].

frequency. The voltage need to be within the range of ±10% of reference value. There is no particular excitation system for hydro generation. For synchronous generator, there are various type of IEEE excitation systems available to be used for stability analysis as described in [64]. The commonly used exciter models reported in the literature are IEEE type AC4A [65,66] and AC5A [64,67]. An example of simplified excitation system adopted in [65] is as shown in Fig. 5. It is important to point out that up to present not much literature described in details regarding the excitation design and voltage transient response. The concern is more towards governor design.

3.2.3. Multiple generators connected in parallel

It is a normal practice to have more than one DG to serve local loads in a distribution system. Some of the DGs which are identical in their design are interconnected in parallel to the same bus feeder. The governor and excitation system have an identical controller thus are capable in sharing the same amount of loads. Meanwhile, certain network system may consist of other types of DG and different capacities of DG interconnect within the vicinity. Practically, when more than one DG is interconnected, they are strongly held to each other, hence are forced to rotate at the same speed or in other words in synchronism to each other. When they are grid connected, the grid strongly holds the frequency and voltage of the system, thus the DG units only have to ensure they dispatch the power as per agreement. However, when the system is islanded, those DGs are responsible to control the frequency and voltage of the island together in order to sustain a stable operation of the island. This definitely requires an advanced control strategy for the DGs to sharing the loads among themselves otherwise they might fight for each other to be a dominant in controlling the whole island.

In the recent years, the issue of controlling multiple numbers of DG units for an islanding operation has become one of the important islanding topics among the researchers. The following are the normal practice in controlling multiple DG units:

1) *Droop mode and droop mode of DG*: The simplest way to control the operation of multiple numbers of DG during islanding operation is to apply droop mode for each of the DG. Using this technique, loads are shared proportionally to the DG's MW capacity. The drawback of this technique is that the island frequency would drop to a new value. The deviation of the frequency from its nominal value will definitely cause deviation in the voltage phase angle as well. Therefore, this technique obviously violates the conditions for grid resynchronization.
2) *Isochronous mode and droop mode of DG*: The second control option is to control the DG units whereby one of the DG is set in isochronous mode whilst the remaining is set in droop mode. The isochronous mode DG tends to dispatch power up to its maximum rating, depending on the changes of the load caused by the transformation from grid connected to islanded mode of operation. It will act as a main speed control unit. Droop mode generator only supply fixed amount of power based on their designated speed changer setting. The highest MVA rated DG is assigned as isochronous DG for serving any load increment when the network is islanded. Excessive load will require load shedding. The advantage of this technique is that the frequency of the island could be recovered to its nominal value. However, this technique will experience the same problem as the first technique if the isochronous mode DG fails to operate during islanding operation. The droop mode generator solely supplies the island causing a drop in the frequency level. This technique has been tested in [68] and [69]. In [68], the islanding operation of two DG units: gas turbine rated at 30 MVA and steam turbine rated at 5 MVA were evaluated. In this case, the gas turbine generator was set in isochronous mode.
3) *Isochronous mode and isochronous mode of DG*: The third control option is to control DG units in the island in isochronous mode. This is as described in [69] where two DG units rated at 4.51 MVA and 2 MVA each were operated in isochronous mode. Communication between DGs was established in the simulation to proportionally share the loads in the island. In this case, no generator acted as a speed control unit. When one of DG trips the remaining DG still can survive and sustain the island to be at its nominal frequency. Obviously, this option required a reliable and fast communication means.

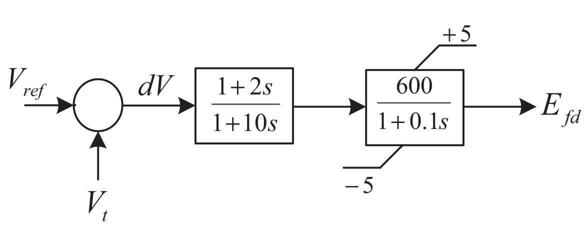

Fig. 5. Automatic voltage regulation (simplified excitation system of IEEE type AC4A) [67].

The above discussed sharing methods are commonly used for synchronous type of DG. For mix types of DG, different approaches are adopted for sharing the loads. The following are the summary of the works done to control mix types of DG:

- In [70], F. Katiraei et al. have investigated the micro-grid operation of two DG units comprised of an inverter type and a synchronous type of DG which each rated at 2.5 MVA and 5.0 MVA respectively. The system was operated at a 13.8 kV distribution system. The authors have adopted a simple control strategy to share the loads between the DG units in a pre-planned islanding. When the system was grid connected, both DGs were set to dispatch the active power based on the pre-specified value (using fixed mode). In islanding operation mode, load sharing technique was implemented by setting the set point of active power for the inverter type of DG to a higher value than during grid connected whilst the synchronous DG supplied to the remaining power demands in the island. The control strategy

was designed such that the total local load is within the generator capacity limit. Thus, no load shedding was required. From the result, it was observed that after the islanding transient, the frequency response of the microgrid recovered to 60 Hz

- In [71], the same authors as in [70] have investigated the operation of three mix types of DG units in a pre-planned islanding. Those DG units are diesel generator, inverter type of DG and wind turbine (attached to induction generator) where each rated at 1.8 MVA, 2.5 MVA and 1.25 MVA respectively. In the study, a control strategy was proposed for reactive/active power sharing among DG units in meeting local load demands in the island. During grid connected, each DG was given a maximum value of pre-specified active power. During islanding operation, the fast respond inverter type of DG was selected to primarily regulate the frequency and active power using the frequency droop characteristic whilst the reactive power and voltage using the voltage droop characteristic. The inverter DG tends to generate the remaining power generated by the synchronous and wind turbine type of DG. The governor of the synchronous DG was controlled to share the active power output with the other DG units. Note that a part of power sharing technique, the influence of wind turbine on the voltage quality and stability of the system was also observed by the authors.
- In another paper [26], the same authors as above have proposed a new control strategy referred as 'power management strategies' which could effectively share the real and reactive power for the two units of inverter type of DG and a synchronous DG in an island. However, the paper emphasized on the small signal dynamic studies and complete design of the inverter type of DG of which not the area of interest in this paper.
- In [25],an islanding operation for three DG units: gas turbine generator, wind farm and diesel generator which each rated at 4.51 MVA, 2.5 MVA and 2 MVA respectively in a 11 kV distribution system was examined. The gas turbine and diesel generator were synchronous type whilst the wind farm is using cascaded induction generators. A comprehensive description on the control strategy and considerations of the islanding process prior to islanding until grid reconnection was presented. An appropriate island management system was introduced considering the possibility of different island configurations. Only gas turbine and diesel generator were controlled for achieving synchronous island. Although the wind farm was not participated in the control system, the effect of its presence to the transient response was determined. The results showed that an equal power sharing among DG units was achieved however the scheme approach was not disclosed in the paper.
- In [72], a power sharing technique for multiple DG units to improve dynamic response in a microgrid was proposed. The microgrid consisted of three parallel connected DG units which are a gas turbine synchronous generator, a wind turbine with double fed induction generator (DFIG) and an inverter type of DG with each rated at 1.8 MVA, 2.5 MVA and 2 MVA respectively. In this study, during islanding mode of operation, the wind turbine was set as a primary frequency control or in other words its controller was designed to be the first priority to response with the changes of the active power in the island. This was due to the quick response of wind turbine to increase its active power output once the system is islanded. The controller was designed with the frequency-droop characteristic. The remaining demand powers in the island were dispatched by the gas turbine and inverter type of generator which were controlled with frequency-droop characteristic and frequency restoration control loop (also known as an isochronous controller). The act of the integration controller helped to restore the system frequency response to its nominal value.

3.3. Islanding operation of small hydro generator

As previously discussed, an islanding operation of DG is feasible with an advanced control system purposely designed to be operated in two modes of operations. However, rotating type of DG which is based on different energy sources such as hydro would require different control design particularly on its governor turbine model. The detail of this model has been reviewed by N. Kishor et al. [7]. The authors have compiled and discussed numerous research works regarding the governor turbine including the types of governor commonly used, finding an optimal value of gains for PID type of governor and modeling of hydro turbine considering linear and/or non-linear with elastic or non elastic water column, the stability performance of the governor under different operating condition, control design considering turbine models and etc. The hydro turbine model would greatly affect the dynamic response of the hydro generation. Most of the works have applied a simple first order linear turbine model [7] to observe the performance of the governor over certain application study. The responses are not too precise but most importantly any advance application such as the islanding operation can be controlled accordingly. As of today, not much works have been reported on an intentional islanding operation for small hydro generation. So far, BC Hydro research group has practically implemented a planned islanding operation on 35 kV and below distribution system and the ongoing research is still taking place to enhance the system operation. The group had developed a distribution DG islanding guideline [73] focusing on the essential considerations, technical issues and operations and safety aspects required for the intentional islanding operation of DG. It highlighted various considerations in every perspective of islanding operation issues of which are very useful to be adopted for any micro-grid/islanding operation. The summary of the guideline is as illustrated in Table 2.

BC Hydro research group has implemented their first islanding operation for the 2×3.6 MVA small hydro power plant in the year 2007 [74]. The main reason to introduce the operation was to improve power reliability to customers. Prior to the event, a proper plan for an islanding operation supplied power to an average load of 3.0 MW was established. The first operation was initiated when the substation feeder breaker received an opening transfer trip signal due to a transmission outage event. The hydro DG was then tripped to initiate black start islanding sequence (note that the DG does not require black start islanding if the plant has enough water to generate power). The operation has been carried out according to the islanding guideline to serve for an approximately 1.1 MW customers load. The operation was successful and persisted for 5 hour. This has resulted in increasing the reliability performance by reducing the SAIFI index from 8.5 to 3.5 h for the year 2008.

Further study on the islanding operation of small hydro generation which was based on the planned islanding experience of BC Hydro and Hydro Quebec were implemented by a group of researchers from Canada in [75]. It is important to highlight that the islanding practices in BC Hydro substation were implemented so far on a single feeder operation (single DG or two identical parallel DG units). This had inspired the authors of the paper to carry out a feasibility study to investigate a planned islanding operation with multiple DG units. The study was based on the BC Hydro substation's configuration. It was performed for two DG units interconnected at two adjacent feeders which rated at 8.6 MVA and 4.4 MVA respectively. Total load in the island is 6 MW. To ensures a smooth islanding operation, two control strategies for the DG's governor and exciter controller were proposed and carried out in the study: (1) Master slave method and (2) Active load sharing method (droop method). For master slave method; during islanded mode of operation, the bigger rated DG was set as a master (isochronous

Table 2
Summary of distribution power generator islanding guidelines as of reference [74].

1	Islanding issues -to be considered and resolved	(1) Islanding scenario: inadvertent or planned islanding (2) System reliability: improved or not (3) Power quality: potential power quality problem (4) Increased cost: additional equipment and associated cost (5) Operation and safety: safety concern during grid reconnection, grounding and protection issues (6) Economic and commercial consideration
2	Reliability	• Distribution reliability indices commonly used: SAIFI and SAIDI • Access the customer based reliability(CBR)
3	Islanding considerations	*DG considerations:* (1) DGs capable to sustain the island by supplying power to the load (2) DGs with broader VAR control for loads to a power factor of ± 0.8 (3) Fast acting speed governor and exciter (4) Inertia and control system to pick up and hold dead load (5) Black start capability (6) Capable to maintain the power quality level for the island (7) Communicate with control centre via real time, communication media which monitor operating data, DG ON/OFF status, primary breaker open/close status and operator communication *BC hydro considerations:* (1) If the feeder's future load is greater than the current island rating, a plan and costing for feeder sectionalization of the excess load is required (2) Line voltage regulators: controls modifications and upgrading (3) Line reclosers: auto on and off, overcurrent bi-directionality and voltage supervised closing (4) Line fuses in grid connected and islanded mode (5) Synchronization: DG with the grid (6) Tasks to incorporate real time DG operating data in the control centre and inter-operator communications (7) Additional staff time to review the design of the plant; additional Control Centre Operator and Local Operating Order procedures; field test the DG for grid connected mode, islanding mode and feeder dead load pickup.
4	Technical issues for islanding	(1) Distribution equipment rating • Revision on the protection equipment rating(fuses, reclosers, sectionalizers, faulted circuit indicators) • Revision on the thermal ampacity of the feeder primary conductor or cable for load flow. • Revision on the voltage regulation for the interconnection point between DG and the BC hydro feeder circuit breaker. (2) DG system grounding • The low voltage side (DG side) for the interconnecting transformer is in delta configuration. The DG unit itself is solidly grounded. (3) DG Capacity and Island Load • The island cannot be sustained if the load in the island is at least twice the islands generation. (4) DG Load Pickup • A direct signal to the DG governor controller is required to switch to the islanding mode and maintain the power quality of the island. • The DG overcurrent protection need to have dual setting: island mode and grid connected mode. • In case of failure of islanding operations on the opening of feeder breaker, then the DG must have: ○ A direct means of voice communication between the control centre and the DG Operator ○ Black start power capability to restart the island operation ○ Appropriate controls, governor, exciter to pick up and hold dead feeder load. • In case of required load shedding, automatic and supervisory control to trip the selected breaker is normally used. (5) DG with support of islanding • This is the case when DG is too small to dispatch power to the island. Another local DG should be considered to support the island together with the DG. (6) BC hydro system equipment Distribution substation equipment for islanding purposes: • Substation feeder circuit breaker: suitably rated • Substation feeder voltage transformer: allow voltage supervised local or remote closing of the substation feeder circuit breaker. • Substation feeder digital protection relays: designed with an advanced features including sync-check, out of step detection and etc. (7) Out of step detection and tripping duty • This is required when a DG and a grid undergo out of step and swing against each other. (8) Transmission line transient overvoltages and transfer trip • Transfer trip to the substation feeder CB is required to disconnect DG from the grid. This is to avoid temporary overvoltage during the clearing of line-to-ground transmission faults. (9) DG control and visibility Requirement to provide operating data and interconnection status to the Control Centre • For DG rated at 1 to 10 MVA: ○ Operating Data: MW, MVAr, MWh and kV ○ Interconnection Status: opened or closed • For DG rated more than 10 MVA: ○ Operating Data: MW, MVAr, MWh and kV; unit connection status and unit running status

Table 2 (*Continued*)

5	Operation and safety	(1) Operation • For a planned islanding operation: additional operating interface are required to ensure smooth operation and customer power quality. ◦ The status data link needs to be real time continuous over dedicated communication link. ◦ Data: Besides MW, MVAr, MWh and kV and interconnection status open/closed CB, additional data i.e. unit Hz and A are also required. • For unplanned event: A direct means for the Area Control Centre person in charge to trip the DG's interconnection CB should be considered to avoid or minimize damage to customers within the feeder island. • Auto-synchronization initiated by the Control Centre to the DG island via the substation feeder breaker may be warranted to avoid unnecessary customers outage during reconnection. (2) Safety • Protection settings need to be changed on the opening of the substation CB; if fail the DG need to be restart and pick up dead load. • For substation reconnection, the closing of feeder CB is defined using the Local Operating Order (LOO). The synch-check relay must identify when the feeder CB can be closed. • Dispatcher and line workers for the feeder require additional training regarding the operation of the DG during a substation outage. • Operating drawings and Control Centre mimics need to indicate when the feeder is operating as an island.

control) whereas another DG unit was set as a slave (fixed control mode as of grid connected pre specified power value). In this case, the isochronous DG accommodated the power mismatch following the islanding. Meanwhile, for active load sharing method; both DG units were set to droop mode. The simulation results for both methods showed that even with slow frequency response of the DG, both methods successfully sustained the island within the power quality level.

In another literature [76], transient analysis of small hydro generators including during an islanding operation of network branches was investigated. The operation of three induction types and four synchronous types of hydro generators with their rating varies from 1.7 MVA and 11.17 MVA connected in a 20 kV distribution network has been examined. Critical Fault Clearing Time (CCT) for short circuit fault studies at different nodes and during islanding operation was identified. Based on the CCT value, the influence of synchronous and induction generator type on the system stability has been identified and distinguished. It was shown that when one of the branches with a maximum loading was temporary islanded, the maximum time the islanded system (without any islanding capability) can stay in-synchronism was 2.4 s following the fault clearing. The study also figured out that the island was unstable when solely run by induction type of DG. This obviously indicated that the induction generator must be first disconnected in the event of fault or islanding.

4. Conclusion

Development of small scale hydro generation are recently increasing thus research on this field including islanding issue are critically needed. This paper has presented a comprehensive review regarding the research works on planned islanding operation for rotating type of DG with a particular focus on small hydro generation. This review has discussed every aspects of islanding operation including control strategies that have been deployed for the operation with rotating type of DGs of which are also a viable solution for hydro generators. A planned islanding operation and an islanding guideline which had been introduced and implemented by BC Hydro were also described in this paper. This operation proves that a planned islanding operation is practically feasible provided that benefits that it can bring outweighs the overall cost involved in changing the conventional distribution system to an automated distribution system. In addition, incorporating a smart grid technology into the distribution system will present greater improvement to the islanding operation performance.

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References

[1] Lopes JAP, Hatziargyriou N, Mutale J, Djapic P, Jenkins N. Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities. Electric Power Systems Research 2007;77:1189–203.
[2] Dalke G, Baum A, Bailey B, Daley JM, Duncan B, Fischer J, et al. Application of islanding protection for industrial and commercial generators-an IEEE industrial application society working group report. In: 59th Annual Conference for Protective Relay Engineers. 2006. p. 12.
[3] IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, IEEE Std 929-2000, 2000.
[4] IEEE Standard for Interconnecting Distributed Resources;1; with Electric Power Systems, IEEE Std 1547-2003, p. 0_1–16, 2003.
[5] Basso TS, DeBlasio R. IEEE 1547 series of standards: interconnection issues. IEEE Transactions on Power Electronics 2004;19:1159–62.
[6] Kundur P. Power system stability and control. McGraw Hill Inc.; 1994.
[7] Kishor N, Saini RP, Singh SP. A review on hydropower plant models and control. Renewable and Sustainable Energy Reviews 2007;11:776–96.
[8] Jiang J. Design of an optimal robust governor for hydraulic turbine generating units. IEEE Transactions on Energy Conversion 1995;10:188–94.
[9] Ichtev A, Puleva T. Multiple-model adaptive control of hydro turbine generator with fuzzy TS models. In: Proceedings of the 9th WSEAS International Conference on Fuzzy Systems, Sofia. 2008.
[10] Eker I. The design of robust multi-loop-cascaded hydro governors. Engineering with Computers 2004;20:45–53.
[11] Foss A, Grandmaitre Y, Kemp W. Enhancing small hydro automation using distributed micro-controllers and simulation. International Journal of Global Energy Issues 2005;24:19–28.
[12] DTI. 2005, Islanded operation of distribution networks.
[13] X. Ding, Synchronized Phasor Measurement and Islanding Operation of Distributed Generation, Doctor of Philosophy, Faculty of Engineering, The Queen's University Belfast, 2006.
[14] Walling RA, Miller NW. Distributed generation islanding-implications on power system dynamic performance. In: Power Engineering Society Summer Meeting, vol. 1, IEEE. 2002. p. 92–6.
[15] IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, IEEE Std 142-2007 (Revision of IEEE Std 142-1991), p. c1–215, 2007.
[16] Electricity Safety, Quality and Continuity Regulations, 2002 (ESQCR) accessed August 2009 from: www.berr.gov.uk/energy/reliability/quality-continuity-upply/regulations/page18957.html.
[17] Mohamad H, Crossley PA. Islanded operation of UK radial distribution: earthing strategy. In: Universities Power Engineering Conference (UPEC), Proceedings of the 44th International. 2009. p. 1–6.
[18] Chaitusaney S, Yokoyama A. Reliability analysis of distribution system with distributed generation considering loss of protection coordination. In: International Conference on Probabilistic Methods Applied to Power Systems (PMAPS). 2006. p. 1–8.
[19] Balaguer IJ, Lei Q, Yang S, Supatti U, Peng FZ. Control for grid-connected and intentional islanding operations of distributed power generation. IEEE Transactions on Industrial Electronics 2011;58:147–57.

[20] Sao CK, Lehn PW. Control and power management of converter fed microgrids. IEEE Transactions on Power Systems 2008;23:1088–98.
[21] Caldon R, Stocco A, Turri R. Feasibility of adaptive intentional islanding operation of electric utility systems with distributed generation. Electric Power Systems Research 2008;78:2017–23.
[22] Blaabjerg F, Teodorescu R, Liserre M, Timbus AV. Overview of control and grid synchronization for distributed power generation systems. IEEE Transactions on Industrial Electronics 2006;53:1398–409.
[23] Bose S, Liu Y, Bahei-Eldin K, de Bedout J, Adamiak M. Tieline controls in microgrid applications. In: Bulk Power System Dynamics and Control – VII. Revitalizing Operational Reliability. 2007. p. 1–9.
[24] Chowdhury SP, Chowdhury S, Crossley PA. Islanding protection of active distribution networks with renewable distributed generators: a comprehensive survey. Electric Power Systems Research 2009;79:984–92.
[25] Best RJ, Morrow DJ, Chui Fen T, Laverty DM, Crossley PA. Management of a multiple-set synchronous island. In: Power & Energy Society General Meeting, 2009, PES09, IEEE. 2009. p. 1–6.
[26] Katiraei F, Iravani MR. Power management strategies for a microgrid with multiple distributed generation units. IEEE Transactions on Power Systems 2006;21:1821–31.
[27] Jiayi H, Chuanwen J, Rong X. A review on distributed energy resources and microgrid. Renewable and Sustainable Energy Reviews 2008;12:2472–83.
[28] Mohamad H, Abu Bakar AH, Ping HW, Mokhlis H. An adaptive controller of hydro generators for smart grid application in Malaysia. In: 2010 International Conference on Power System Technology (POWERCON). 2010. p. 1–6.
[29] Strath N. Islanding detection in power systems. Lund University: Department of Industrial Electrical Engineering and Automation; 2005.
[30] Jun Y, Liuchen C, Diduch C. Recent developments in islanding detection for distributed power generation. In: 2004 Large Engineering systems Conference on Power Engineering, LESCOPE-04. 2004. p. 124–8.
[31] Menon V, Nehrir MH. A hybrid islanding detection technique using voltage unbalance and frequency set point. IEEE Transactions on Power Systems 2007;22:442–8.
[32] Francesco De M, Marco L, Antonio DA, Alberto P. Overview of anti-islanding algorithms for pv systems. Part I: passive methods. In: Power Electronics and Motion Control Conference, 2006. EPE-PEMC, 12th International. 2006. p. 1878–83.
[33] Zhihong Y, Kolwalkar A, Yu Z, Pengwei D, Reigh W. Evaluation of anti-islanding schemes based on nondetection zone concept. IEEE Transactions on Power Electronics 2004;19:1171–6.
[34] Zeineldin HH, Abdel-Galil T, El-Saadany EF, Salama MMA. Islanding detection of grid connected distributed generators using TLS-ESPRIT. Electric Power Systems Research 2007;77:155–62.
[35] Bright CG. COROCOF: comparison of rate of change of frequency protection. A solution to the detection of loss of mains. In: Seventh International Conference on (IEE) Developments in Power System Protection. 2001. p. 70–3.
[36] Ishibashi A, Imai M, Omata K, Sato S, Takagi T, Nakachi Y, et al. New type of islanding detection system for distributed generation based on voltage angle difference between utility network and distributed generation site. In: Eighth IEE International Conference on Developments in Power System Protection, vol. 2. 2004. p. 542–5.
[37] Zeineldin HH, El-Saadany EF, Salama MMA. Islanding detection of inverter-based distributed generation. Generation, Transmission and Distribution, IEE Proceedings 2006;153:644–52.
[38] Vieira JCM, Freitas W, Wilsun X, Morelato A. Performance of frequency relays for distributed generation protection. IEEE Transactions on Power Delivery 2006;21:1120–7.
[39] Allan R, Jenkins N, Crossley P, Kirschen D. Embedded generation. IEE power and energy series. London: The Institution of Electrical Engineers; 2000.
[40] Ding X, Crossley PA. Islanding detection for distributed generation. IEEE Power Tech 2005.
[41] Freitas W, Wilsun X, Affonso CM, Zhenyu H. Comparative analysis between ROCOF and vector surge relays for distributed generation applications. IEEE Transactions on Power Delivery 2005;20:1315–24.
[42] Affonso CM, Freitas W, Xu W, da Silva LCP. Performance of ROCOF relays for embedded generation applications. IEE Proceedings-Generation, Transmission and Distribution 2005;152:109–14.
[43] Rajabi-Ghahnavie A, Parniani M, Fotuhi-Firuzabad M. Investigating the effects of reactive power on islanding detection. In: International Conference on Power System Technology, PowerCon, vol. 2. 2004. p. 1067–71.
[44] Ackermann T, Knyazkin V. Interaction between distributed generation and the distribution network: operation aspects. In: Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES, vol. 2. 2002. p. 1357–62.
[45] Redfern MA, Usta O, Fielding G. Protection against loss of utility grid supply for a dispersed storage and generation unit. IEEE Transactions on Power Delivery 1993;8:948–54.
[46] Fu-Sheng P, Shyh-Jier H. A detection algorithm for islanding-prevention of dispersed consumer-owned storage and generating units. IEEE Transactions on Energy Conversion 2001;16:346–51.
[47] Kim JE, Hwang JS. Islanding detection method of distributed generation units connected to power distribution system. In: International Conference on Power System Technology, 2000. Proceedings, PowerCon, vol. 2. 2000. p. 643–7.
[48] Sung-Il J, Kwang-Ho K. Development of a logical rule-based islanding detection method for distributed resources. In: Power Engineering Society Winter Meeting, vol. 2 IEEE. 2002. p. 800–6.
[49] Salman SK, King DJ, Weller G. New loss of mains detection algorithm for embedded generation using rate of change of voltage and changes in power factors. In: 2001, Seventh International Conference on (IEE) Developments in Power System Protection. 2001. p. 82–5.
[50] Sung-Il J, Kwang-Ho K. An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current. IEEE Transactions on Power Delivery 2004;19:745–52.
[51] Ko AD, Burt GM, Galloway S, Booth C, McDonald JR. UK distribution system protection issues. Generation, Transmission & Distribution, IET 2007;1:679–87.
[52] Freitas W, Zhenyu H, Xu W. A practical method for assessing the effectiveness of vector surge relays for distributed generation applications. In: Power Engineering Society General Meeting, 2004, vol. 1, IEEE. 2004. p. 821.
[53] O'Kane P, Fox B. Loss of mains detection for embedded generation by system impedance monitoring. In: Sixth International Conference on (Conf. Publ. No. 434) Developments in Power System Protection. 1997. p. 95–8.
[54] Renewable UK., 2010 Vestas and DONG bosses hail record UK wind deployment accessed November 2010 from: http://www.bwea.com/media/news/articles/pr20100923-1.html.
[55] Marketing Working Group: TNSHP, 2004, Small Hydropower Situation in The New EU Member States And Candidate Countries accessed November 2010 from http://www.esha.be/fileadmin/esha_files/documents/publications/publications/Report_on_SHP_in_New_European_Member_States.pdf'.
[56] Paish O. Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews 2002;6:537–56.
[57] Doolla S, Bhatti TS. Automatic generation control of an isolated small-hydro power plant. Electric Power Systems Research 2006;76:889–96.
[58] Trujillo CL, Velasco D, Figueres E, Garcerá G. Analysis of active islanding detection methods for grid-connected microinverters for renewable energy processing. Applied Energy 2010;87:3591–605.
[59] Conti S, Greco AM, Messina N, Vagliasindi U. Generators control systems in intentionally islanded MV microgrids. In: International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM. 2008. p. 399–405.
[60] Mahon LLJ. Diesel generator handbook. Oxford: Butterworth-Heinemn; 1992.
[61] Best RJ, Morrow DJ, McGowan DJ, Crossley PA. Synchronous islanded operation of a diesel generator. IEEE Transactions on Power Systems 2007;22:2170–6.
[62] Lin G, Junrong X, Yiping D. Analysis of power system frequency responses with hydro turbines incorporating load shedding. In: 2010, the 5th IEEE Conference on Industrial Electronics and Applications (ICIEA). 2010. p. 893–7.
[63] Hydraulic turbine and turbine control models for system dynamic studies. IEEE Transactions on Power Systems 1992;7:167–79.
[64] IEEE Std 421.5-2005 IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Std 421. 5-2005 (Revision of IEEE Std 421.5-1992), pp. 0_1-85, 2006.
[65] Calderaro V, Milanovic JV, Kayikci M, Piccolo A. The impact of distributed synchronous generators on quality of electricity supply and transient stability of real distribution network. Electric Power Systems Research 2009;79:134–43.
[66] Hirodontis S, Li H, Crossley PA. Transient responses of distributed generators in islanded operation. In: International Conference on Sustainable Power Generation and Supply, SUPERGEN. 2009. p. 1–5.
[67] Quinonez-Varela G, Cruden A. Experimental testing and model validation of a small-scale generator set for stability analysis. In: Power Tech Conference Proceedings, 2003 IEEE Bologna, vol. 3. 2003. p. 5.
[68] Chilvers IM, Milanovic JV. Comparative analysis of transient operation of two different embedded gas turbine power plants. In: Presented at the 14th Power System Computation Conference, PSCC, Sevilla, June. 2002.
[69] Ten CF, Crossley PA. Control of multiple distributed generators for intentional islanding. In: SmartGrids for Distribution, 2008. IET-CIRED, CIRED Seminar. 2008. p. 1–4.
[70] Katiraei F, Iravani MR, Lehn PW. Micro-grid autonomous operation during and subsequent to islanding process. IEEE Transactions on Power Delivery 2005;20:248–57.
[71] Katiraei F, Iravani MR. Transients of a micro-grid system with multiple distributed energy resources. In: International Conference on Power Systems Transients (IPST'05). 2005.
[72] Shahabi M, Haghifam MR, Mohamadian M, Nabavi-Niaki SA. Dynamic behavior improvement in a microgrid with multiple DG units using a power sharing approach. In: PowerTech, 2009 IEEE Bucharest. 2009. p. 1–8.
[73] BCHydro 2006, Distribution power Generator Islanding Guideline accessed November 2010 from: www.bchydro.com.
[74] Peralta J, Iosfin H, Tang X. BC Hydro perspective on distribution islanding for customer reliability improvement. In: Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium. 2009. p. 1–2.
[75] Katiraei F, Abbey C, Tang S, Gauthier M. Planned islanding on rural feeders-utility perspective. In: Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE. 2008. p. 1–6.
[76] Dagoumas A, Lettas N, Tomaras K, Papagiannis G, Dokopoulos P, Zafirakis A, et al. Transient analysis of distributed small hydro generators in a network. In: 2005 International Conference on Future Power Systems. 2005. p. 1–6.